A simple way to design NARROWBAND INTERDIGITAL FILTERS

by
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HERE IS a simple way to design high-quality bandpass filters for vhf, uhf or microwaves, to your own requirements. Compared with the old-fashioned "high-Q-break" using a single sharply-tuned circuit, filters using multiple tuned circuits have flatter passbands (ie less critical tuning), steeper skirts and better attenuation in the stopband. Filters of this type are reputed to be difficult to design and to build, but this article will show how easily it can be done, using nothing more exotic than a scientific calculator and a drill-press.

Fig 1 shows the layout of an "interdigital" filter using four tuned circuits. The tuned circuits or "resonators" take the form of rods which are almost a quarter-wavelength ($\lambda/4$) long. Alternate resonators are mounted on opposite sides of the box, like interlinked fingers of opposite hands (which is why filters of this type are called "interdigital"). The minimum number of resonators for an interdigital filter is two, and this article gives design data for filters with two, three or four resonators.

Although interdigital filters can be designed with extremely wide and flat passbands, the calculations are difficult and the component dimensions required are very odd; this is why such filters are reputed to be "too hard" for radio amateurs. But for amateur radio purposes we seldom need bandwidths of more than a few per cent of the centre frequency, and we are usually prepared to tolerate some other deviations from theoretical perfection. The design and construction of interdigital filters then becomes quite simple. A few minutes' work with a calculator provides all the dimensions for a filter to your own requirements, and all the components are made from standard sizes of round rod, rectangular bar and flat sheet. No difficult machining is involved: the "special" dimensions which determine the performance of the filter are achieved simply by drilling a few holes in the right places along a straight line.

The design procedure in this article was first described by M. Dishal of ITT Federal Labs in 1965 [1]. Dishal realized that the design of interdigital filters can be simplified if very wide bandwidths are not required and if some lapses from theoretical perfection can be accepted. For amateur radio purposes that is a fair trade-off. This article follows Dishal's method but leaves out his justifications for the simplifications, so it would be advisable to read [1] before departing from the design procedure given here.

Choosing a filter

The whole design procedure is summarized in the box on page 122, and the best way to understand it is to work through an example.

The first step in any design procedure is to decide what you want. This example shows how to design a filter for the output of a 28–432MHz transverter: let us say that the 404MHz local oscillator feedthrough is to be attenuated by an extra 40dB, and the passband must be flat (within about 1dB) across the whole band from 432 to 438MHz. In amateur radio exact specifications such as these are largely a matter of personal choice: for example, you might decide to relax the attenuation specification by a few decibels if the paper design study suggested that the filter might then be easier to build.

The centre frequency of the filter is 435MHz. For this design procedure the bandwidth has to be specified at the −3dB points, so try setting them at ±8MHz, ie at 427 and 443MHz (see later). The fractional bandwidth w is defined as:

$$w = (-3\text{dB bandwidth})/(\text{centre frequency})$$

In this case $w = (2 \times 8\text{MHz})/(435\text{MHz}) = 0{\cdot}0368$. This is about the right order of fractional bandwidth for Dishal's design procedure: the simplifying approximations remain valid for fractional bandwidths up to about 0·1, and the effects of losses and constructional imperfections become very marked at fractional bandwidths less than about 0·01.

The −40dB bandwidth is $2 \times (435-404)\text{MHz} = 62\text{MHz}$, and since the −3dB bandwidth is $2 \times 8\text{MHz} = 16\text{MHz}$, the (−40dB/−3dB) shape factor of the filter is the ratio of the respective bandwidths: 3·875.

Now look at Fig 2, which shows stopband attenuation as a function of shape factor [2]. Fig 2 is for perfect Butterworth [3] filters with no component losses, and shows that filters with more resonators give better stopband attenuation (although of course they involve more mechanical work). In the present worked example a filter with only two or three resonators cannot meet the shape/attenuation specification of 3·875 at −40dB, but four resonators can.

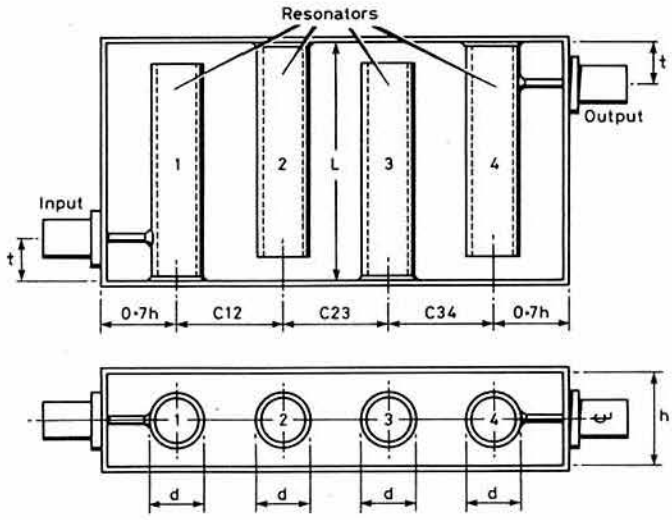

Fig 1. Four-resonator interdigital filter

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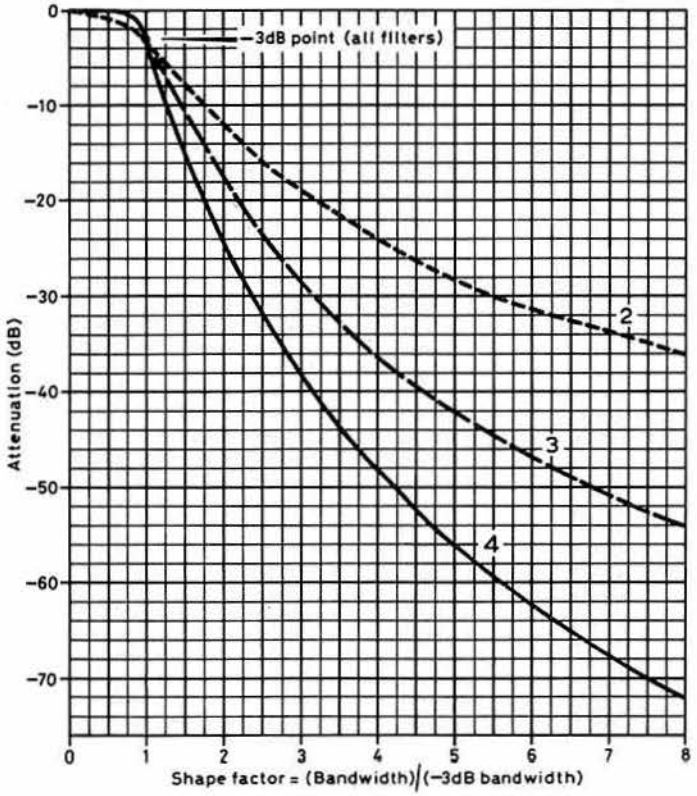

Fig. 2. Responses of lossless Butterworth filters with 2, 3 and 4 resonators

Fig 2 is for perfect filters, and a real filter will have poorer stopband attenuation, greater inband insertion loss, and more rounded shoulders to its passband. How closely the finished filter will approach theoretical perfection depends very much on the care taken in construction; and if any of the above factors is critical in your particular application, now is the time to review the tentative specifications of bandwidth and shape factor. For example, a flatter passband could be achieved by widening the design bandwidth, though only at the expense of stopband attenuation. This in turn could be improved by using more resonators, but then the insertion loss would increase. Thus it is important to have a clear idea of what you really need from the filter, and be prepared to compromise on the less essential features.

Ks and Qs

The four resonators are arranged as shown in Fig 1, and are numbered 1-4. The desired frequency response will be created by controlling the coupling coefficients between adjacent resonators (K12 between resonators 1 and 2; K23; and K34), and by controlling the loaded Qs of resonators 1 and 4.

Table 1 gives the coupling coefficients and resonator Qs for two-, three- and four-resonator filters [2]. There are three things to note about the values in Table 1. First, all the filters are symmetrical: values for the first resonator are the same as those for the last, and so on. Second, only the first and last resonators have loaded Qs less than infinity. Finally, Table 1 does not directly give values for Ks and Qs, for these will depend on the selected fractional bandwidth w; instead Table 1 gives "universal" values called "k" and "q". To obtain the required values of the Ks and Qs, multiply the k values by w, and divide the qs by w. In this example:

K12 = K34 = 0·840 × 0·0368 = 0·0309
K23 = 0·542 × 0·0368 = 0·0199
Q1 = Q4 = 0·766/0·0368 = 20·82
Q2 = Q3 = infinity

Dimensions

Leaving the calculator aside for a moment, think ahead to the construction stage. The filter consists of the resonators and the containing box. Brass or copper are the best materials, and you can design the filter to be made from stock sizes of rod and bar. All the resonators are made from plain round rod of the same diameter d (Fig 1). The side and end walls of the box are made from rectangular bar, the width of which determines the internal

Table 1. Design data for filters with two, three and four resonators

No of resonators	Two	Three	Four
q1	1·414	1·000	0·766
q2	1·414	Infinity	Infinity
q3	—	1·000	Infinity
q4	—	—	0·766
k12	0·707	0·707	0·840
k23	—	0·707	0·542
k34	—	—	0·840

height h of the box. Within reasonably wide limits the actual values of d and h do not matter: the important thing is the ratio between the two. Rods of 9·52mm (0·375in) diameter and 19·5mm (0·75in) wide bar are often convenient sizes, and will be used in this example. The ratio d/h (Fig 1) is thus 0·50.

Remember that you are not restricted to having to use those particular dimensions, or even that d/h ratio. The beauty of Dishal's design procedure is that you can build a filter to the same performance specification from a wide range of material sizes, because the formulas below let you work out the dimensions according to the performance you want and the materials you wish to use.

Spacings

The spacing c required to achieve a coupling coefficient K between two round resonators in an interdigital filter is given by the formula:

$$c = [0{\cdot}91\ (d/h) - \log K - 0{\cdot}048]h/1{\cdot}37$$

which is easy enough to work out on a scientific calculator. In this example, c12 = c34 = 26·7mm, and c23 = 29·4mm.

Unlike some types of interdigital filter, this design has to have end walls, and the spacing from the centres of resonators 1 and 4 to the end walls must be 0·7h; in this case 13·4mm. The total length of each side bar is thus:

$$0{\cdot}70h + c12 + c23 + c34 + 0{\cdot}70h = 109{\cdot}5\text{mm}.$$

Mark out all the resonator locations and the total length along the *centre-line* of one bar, as accurately as you can. Clamp the two bars together and drill pilot holes square through all the locations in both bars. Face off the ends of the bars to make an identical pair, and open out the holes to appropriate sizes for resonator retaining screws or for tuning screws.

Rods and tuning screws

The inside width of the box is approximately λ/4 at the centre frequency, ie 172mm at 435MHz, although this is not a critical dimension. In many designs the resonators are themselves almost λ/4 long and are fixed-tuned by their capacitance to the opposite sidewall. This makes it difficult to estimate the correct lengths, and for one-off filters it is easier to deliberately cut the resonators a little short and adjust them to resonance using capacitive tuning screws. At microwave frequencies the resonators can be as short as 0·90 (λ/4), but at uhf the tuning range of a screw is limited so the 435MHz resonators should be cut to 0·95 (λ/4), ie 164mm. Minor errors in resonator lengths can be "tuned out" by the screws, and the whole response of the filter can be shifted several megahertz if necessary.

End walls and matching

The presence of the end walls makes resonators 1 and 4 look like "trough-lines" whose impedance Z is given by:

$$Z = 138 \log(1{\cdot}25h/d)$$

For a d/h ratio of 0·5, Z is 55Ω. Input/output matching is a simple matter of tapping up the line at the right place. The height t of the input and output taps on resonators 1 and 4 (Fig 1) depends on the impedance R of the external system (usually 50Ω) and the loaded Q already calculated from Table 1. t is given by the formula:

$$t = (L/90)\arcsin\sqrt{R\pi/4ZQ}$$

assuming your calculator works in degrees and not radians. The length L in this formula should be the electrical rather than the mechanical length of the resonators, ie λ/4. Substituting the figures for the design example into the formula gives:

$$t = (172/90)\arcsin\sqrt{50\pi/(4 \times 55 \times 20{\cdot}83)} = 20{\cdot}4\text{mm}$$

Final assembly

So now you have all the dimensions and can start assembling the filter. Fig 3 gives some suggestions for constructional methods. The top and bottom covers should be flat and rigid, and can be made of sheet brass or copper, or even copper-clad printed-circuit board with external stiffening. *Make sure that everything goes together symmetrical, square and parallel* because this affects the Qs of the resonators and the overall performance of the filter. At lower frequencies (including 435MHz) the resonators may need

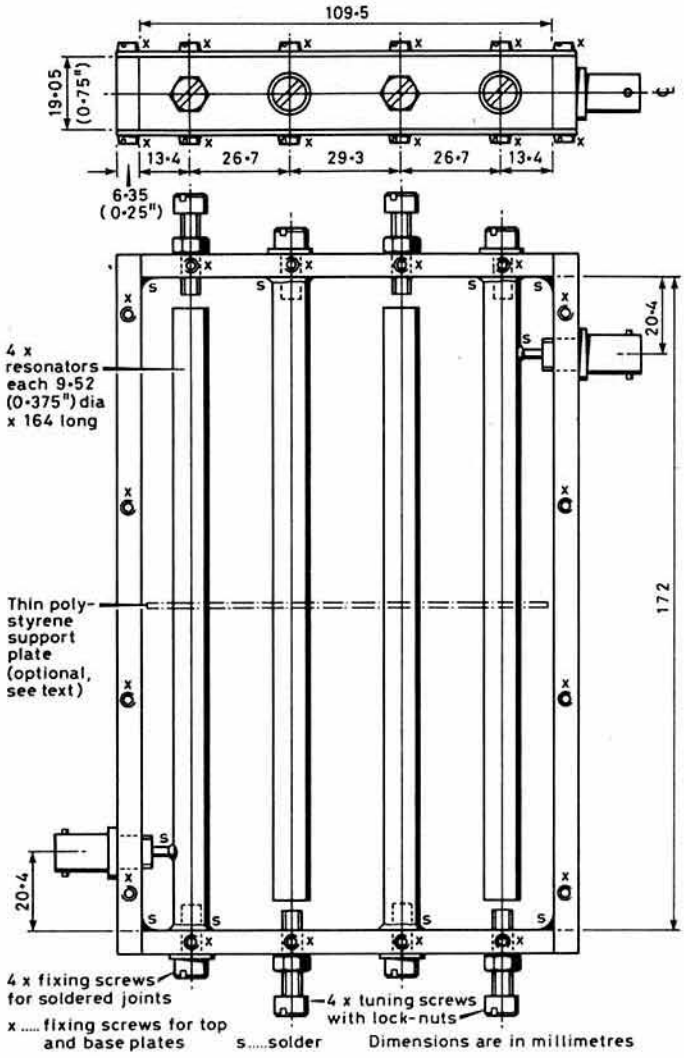

Fig 3. Final dimensions and suggestions for construction of the filter in the worked example

some additional support; this can be provided by a thin plate of low-loss material such as polystyrene, accurately drilled for pilot holes at the same time as the two side bars. The plate should be at the mid-points of the resonators (Fig 3) and not at the free ends where dielectric losses would be greater.

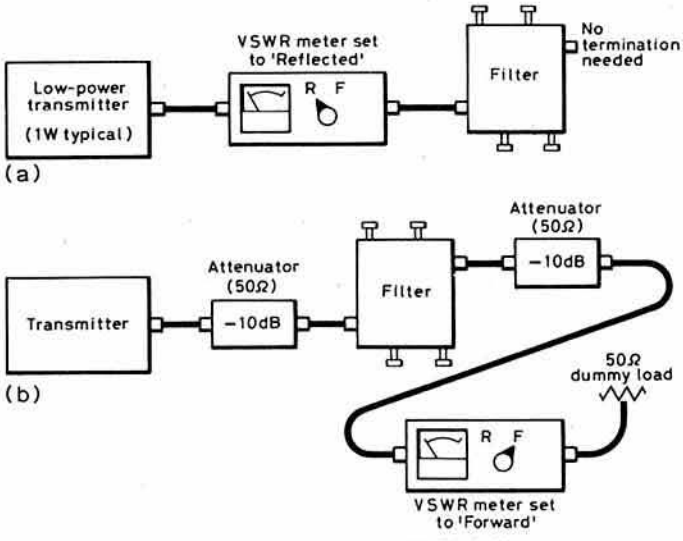

Fig 4. (a) Preliminary alignment. (b) Final alignment

SUMMARY OF DESIGN PROCEDURE

1. Choose the centre frequency and −3dB frequencies, and calculate the fractional bandwidth w.
2. Choose the required stopband performance (attenuation versus frequency).
3. Find the number of resonators required, using Fig 2. If necessary, repeat steps 1 and 2.
4. Look up the ks and qs in Table 1, and calculate the Ks and Qs.
5. Choose the rod diameter d and wall height h.
6. Calculate all spacings c along the side bars.
7. Length L is λ/4. Choose the resonator length in the range 0·95L (uhf) to 0·90L (microwaves).
8. Calculate the position t of the input and output tapping points.
9. Build the filter and tune it up.

The joints between the resonators and the side bars *must* be square and solid. A lathe would be useful to face-off the end of each rod and to drill and tap it for a retaining screw, but the job can be done by hand. RF currents flow across the joints between the rods and the side bars, and any losses here can seriously degrade the Qs of the resonators, so tighten each rod squarely against the bar. Ideally the joints should be silver-soldered for the lowest losses; possibly the next best alternative is to make the ends of the resonators slightly concave, leaving a sharp outer ring which bites into the side bars when the joint is drawn up tight. Otherwise the joint can be soft-soldered, but on no account should it be left as a plain butt joint. It is also important to use plenty of screws for the top and bottom covers, especially above and below the fixing points for the resonators, and 6·35mm (0·25in) is a convenient thickness for ease of drilling and tapping the side and end bars. When you are completely happy [4] with the filter you could silver-plate and polish it for a closer approach to theoretical perfection.

Tune-up

If you connect the newly-built selective filter into circuit and feed a signal into it at the passband frequency, the chances of seeing any output at the other side are zero! All the tuning screws must be quite close to their final settings before you can see enough output to peak everything up. Dishal offers a clever way of completely aligning the filter using a slotted line (or nowadays a network analyser), so if you have access to such equipment then read [1] and go to it.

Lacking a slotted line or a network analyser, the filter can still be aligned quite well with the aid of an ordinary vswr meter. Connect the meter as shown in Fig 4(a), and short all resonators except No 1 by running their tuning screws fully in. With the vswr meter set to "reflected", carefully adjust tuning screw No 1 until the meter needle flickers, and lock the screw at that point. Now do the same with tuning screw No 2. At this stage you can either proceed through to Nos 3 and 4, or reverse the filter and tune 4 followed by 3. The entire filter is now close to resonance, and you should be able to detect a signal through it.

Place the filter between 50Ω attenuator pads (Fig 4(b)) to establish the correct source and load impedances, and complete the alignment. Being a symmetrical Butterworth design, the filter should have the correct response when simply peaked at the centre frequency, and should also have a low in-band insertion swr. It is hard to avoid the temptation to re-peak the filter after installation, but if excessive retuning is required the fault may lie in incorrect source and terminating impedances elsewhere in the system.

Having followed this design procedure, you should now have an interdigital filter with passband and stopband characteristics close to those *you* wanted.

References and notes

[1] "A simple design procedure for small percentage bandwidth round-rod interdigital filters." M. Dishal, *IEEE Trans*, vol MTT-13, September 1965, pp696–8.

[2] *Reference Data for Radio Engineers.* ITT/Sams, various editions. ISBN 0-672-21218-8.

[3] Fig 2 and Table 1 are for Butterworth filters because these are the easiest to align using minimal test equipment. The insertion loss and vswr of the Butterworth filter are always lowest in the middle of the passband, so simply peaking the response at that frequency should ensure nearly correct alignment.

[4] Of course, a real experimenter is never completely happy with *anything* he builds. Like all true works of art, his projects are never finished, but merely abandoned or re-used. And that is why there is no photograph of the completed filter: it was designed and built, did its job while it was needed, and then was re-absorbed into the junk box! □